Research and Development Laboratories
of the
Portland Cement Association

RESEARCH DEPARTMENT
Bulletin 99

The Use of Air-Entraining Admixtures In Concrete In Large Dams In the United States

By

William Lerch

DECEMBER, 1958
CHICAGO

Reprinted from *R 98*, Sixth Congress on Large Dams, New York City, September 1958

COMMISSION INTERNATIONALE
DES GRANDS BARRAGES
de la Conférence Mondiale de l'Énergie

R. 98

QUESTION N° 23

SIXIÈME CONGRÈS
DES GRANDS BARRAGES
NEW YORK, 1958

W. LERCH
(U. S. A.)

THE USE OF AIR-ENTRAINING ADMIXTURES IN CONCRETE IN LARGE DAMS IN THE UNITED STATES (*).

WILLIAM LERCH,

Head, Performance Tests Group, Portland Cement Association, Chicago, Illinois.

Laboratory studies of air-entraining admixtures and air-entrained concrete were initiated in the United States about 1937. These early studies were directed primarily toward providing concrete for use in pavements that would have improved resistance to freezing and thawing and resistance to the surface scaling that results from the application of salts (sodium chloride and calcium chloride) for the removal of snow and ice. A number of experimental road projects were constructed using air-entrained concrete during the years 1938 to 1942. Several different air-entraining agents were used in these laboratory tests and experimental road projects. The results obtained clearly demonstrated the superior resistance to freezing and thawing and resistance to surface scaling of the air-entrained concrete [1], [2], [3], [4] (1). The use of air-

(*) *L'utilisation d'agents entraîneurs d'air dans le béton des grands barrages de États-Unis.*

(1) Numbers in parentheses refer to the list of references appended to this paper.

entrained concrete in pavements and structures has increased rapidly since 1942.

As the properties of air-entrained concrete became established by laboratory tests and field experience, it became apparent that such concrete had many advantages for use in large dams. The first use of an air-entraining admixture in a large dam in the United States to produce purposeful air-entrained concrete of controlled air content, was in Blue Stone Dam, West Virginia, constructed in 1946 to 1947 by the U. S. Corps of Engineers. It is probable that some dams constructed prior to that time did contain a limited quantity of unintentionally entrained air. The air was incorporated in the concrete, unknowingly at the time, through the use of portland cements containing oil or grease leaking from the finish grinding mill or through the use of admixtures that were incorporated in the concrete mixtures as water-reducing agents.

Laboratory tests and field experience have clearly demonstrated that air-entrained concrete has many technical and economical advantages for use in mass concrete. The use of air-entraining admixtures in concrete for large dams has increased rapidly since 1946 and such admixtures have been used in all large concrete dams constructed in the United States in recent years. The performance of air-entrained concrete has fully justified its use. The use of air-entraining admixtures improves the workability of concrete and has made it possible to place concrete of lower cement content in the construction of large dams. The resultant use of lower cement contents decreases the temperature rise within the mass. It has brought about changes in the type of cement used and in construction procedures.

AIR-ENTRAINING ADMIXTURES.

Air-entraining admixtures are materials that incorporate small, discrete, stable air bubbles in the concrete during mixing. They are used in very small quantities, usually less than 0.05 % by weight of the cement. There are a large number of materials that can be used as air-entraining admixtures. They include the following general types of materials :

1. Natural wood resins, such as rosin;
2. Animal or vegetable fats and oils, such as tallow, fish oil, and their fatty acids, such as stearic and oleic acid;
3. Various wetting agents such as alkali salts, of sulfated and sulfonated organic compounds;
4. Water-soluble soaps of resin acids and animal and vegetable fatty acids.

The air-entraining admixtures used in the United States are those meeting the requirements of the specifications of the American Society

for Testing Materials [5]. Some materials that entrain air would not produce concrete meeting the requirements of that specification.

Air-entraining cements are available in most areas of the United States and such cements are used extensively in the construction of pavements and structures. Air-entraining admixtures are generally used, in preference to air-entraining cements, to produce air-entrained concrete for large dams. The use of air-entraining admixtures provides the best means of controlling the air content for the kind of concrete that is used in large dams.

WORKABILITY, BLEEDING AND SEGREGATION.

Entrained air greatly improves the workability of the concrete, and decreases bleeding and segregation. Because of the improved workability it is possible and desirable to reduce the sand content of a mix in a quantity approximately equal to the volume of entrained air. Entrained air provides a means of designing workable concrete mixtures of lower water-cement ratio and lower cement content than can be obtained when using the same materials without the entrained air. The reduction in cement content provides a definite economical advantage in the construction of large concrete dams.

STRENGTH.

The strength of air-entrained concrete (at a constant air content) is principally dependent on the water-cement ratio. Thus an air-entrained concrete mixture can be designed to provide any desired strength in a manner similar to non-air-entrained. For concretes having the same cement content, air-entrainment tends to reduce the strength for rich mixtures. With lean mixtures, such as those used in large concrete dams (4 sacks/cu. yd. or less), air-entrainment is accompanied by relatively larger reductions in water requirement and for these mixtures the strengths will not be reduced, they may even be increased, by the use of air-entrainment.

RESISTANCE TO ABRASION.

Compressive strength is the most important factor controlling the resistance of concrete to abrasion; the resistance increases as the compressive strength increases. The air content of the concrete influences its resistance to abrasion only insofar as it affects the compressive strength. In other words, air-entrained concretes are as resistant to abrasion as plain concretes provided they are designed for equal strength [6].

RESISTANCE TO FREEZING AND THAWING.

Concrete dams are often constructed at high elevations or in northern climates where they are exposed to severe weather conditions and numerous cycles of freezing and thawing. Previous experience has shown that the durability of non-air-entrained concrete dams, particularly thin dams such as multiple arches and Ambursen type, can be seriously affected by freezing and thawing [7], [8], [9], [10].

Laboratory tests and field exposure studies have shown that a high resistance to freezing and thawing cannot be obtained through the selection of cement composition or fineness or by cement content or slump of non-air-entrained concrete having water-cement ratios encountered in present-day practice. High resistance to freezing and thawing can be obtained with air-entrained concrete. Extensive studies conducted in the Research Laboratories of the Portland Cement Association confirm these points [11]. The cements used in one of these studies were made at five different plants from clinker which in composition represented two of American Society for Testing Materials Type I and one each of Types II, III and IV cements. At each plant three grinds were made from the same batch of clinker-coarse, medium and fine. By proper blending of these grinds, cements having finenesses of 1 400, 1 800 and 2 200 sq. cm/g, turbidimeter method, were obtained for test.

These non-air-entraining cements were used in the preparation of concretes having cement contents of 4,5 1/2 and 7 sk./cu. yd. The net water-cement ratio of the concretes ranged from a low of 4.6 to a high of 8.8 gal./sk. The Type II cements of each fineness were used also with varying additions of an air-entraining admixture to obtain air-entrained concretes. Specimens prepared from these concretes were subjected to freezing and thawing tests in the laboratory. The specimens were cured in a moist atmosphere for 28 days and then soaked in water for three days prior to freezing and thus were particularly vulnerable to damage from the freezing of water in the pores.

The curve in figure 1 is based on data from these freezing and thawing tests. It shows that all of the non-air-entrained concretes had low resistance to freezing and thawing regardless of composition or fineness of the cements or cement content or water-cement ratio of the concretes. They all attained an expansion of 0.10 % in 110 cycles, or less, of freezing and thawing. On the other hand, as the air content of the concrete was purposely increased by the use of an air-entraining admixture, the resistance to freezing and thawing likewise increased. The concretes having air contents of 3.0 to 6.0 % had not expanded 0.10 % even after 1 250 cycles of freezing and thawing. These results clearly demonstrate that the air content of the concrete is of far more significance with regard to frost resistance than the fineness or composition of the cement. Cements of different composition and fineness were used also on experimental pavement projects [3], [4]. A high resistance

to freezing and thawing was not attained with any of the cements in non-air-entrained concrete. It was attained only by the use of air-entrainment.

In another series of tests, 27 different cements were used in the preparation of box-type specimens 30 inches square, cast in place and filled

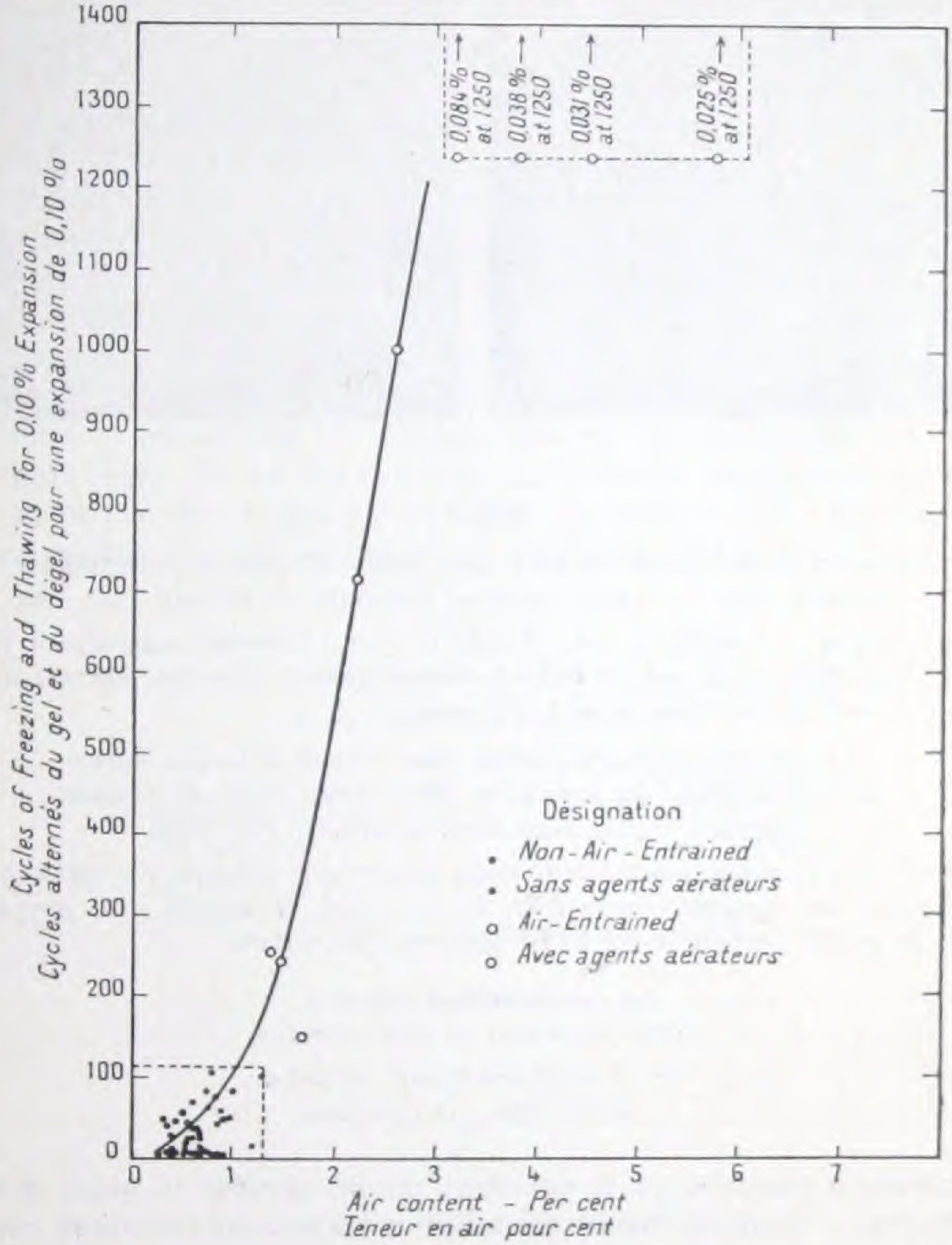

Fig. 1.

Relative effect of cement composition and fineness and of entrained air on resistance to freezing and thawing.

Effet relatif de la constitution et de la finesse du ciment et de l'air entraîné sur la résistance au gel et dégel.

with sand and water. Six different mixes and two combinations of aggregates were used in the construction of the boxes [12]. The benefit of air-entrained concrete in resisting severe weathering is clearly shown by the performance of these boxes at the Portland Cement Association

Naperville, Illinois Test Plot. Figure 2 illustrates the relative performance of boxes made with a Type II cement and an air-entraining cement made from the same clinker. Many similar comparisons are available on the test plot. Without exception, the boxes made with

a *b*

Fig. 2.

Views of boxes from the long-time study of cement performance in concrete after 16 years' outdoor exposure at Illinois Test Plot.

Cement content : 6 sacks/cu. yd.; slump, 1 1/2 in., vibrated; aggregates, Springville, New York sand, and Plainfield, Illinois gravel. In the concrete in these boxes a sand of doubtful quality was used.

Aspects des blocs-échantillons pour l'étude à longue durée du comportement du ciment en béton après avoir été exposés pendant 16 ans sans abril à Illinois Test Plot.

Teneur en ciment : 6 sacs par année cubique; affaissement (slump), 1 1/2 pouce; vibrés; provenance des agrégats, Springville, N. Y. sable; Plainfield, Ill. gravier. Un sable de qualité douteuse a été utilisé dans ces échantillons.

(*a*) Air-entrained concrete.
Béton contenant de l'air entraîné.

(*b*) Non-air-entrained concrete.
Béton sans air entraîné.

air-entrained concrete are in excellent condition after 16 years of severe weathering. Many of the boxes made with non-air-entrained concrete are showing advance stages of deterioration.

PERMEABILITY AND PORE PRESSURE.

The permeability of well-designed mass concretes, even with mixes as lean as 2 sacks of cement per cubic yard, is so low as to indicate that equilibrium pore pressures are not likely to be achieved in a moderate number of decades, if ever. The effect of entrained air is found not only to reduce the permeability of concrete but also to delay the pene-

tration of water into a dam by a factor of several times, by virtue of the water capacity of the air voids [13].

OPTIMUM AIR CONTENT.

The optimum air content of the concrete is considered to be that minimum air content beyond which further increases in air result in only a marginal further improvement in resistance to freezing and thawing. This air content is optimum in the sense that it is, in general, a balance point between increase in durability and reduction in strength and reduction in unit weight. Laboratory tests have shown that the optimum air content of concrete can be expressed as the air content of the mortar fraction or as the air content of the entire mix. The tests have shown that an air content of 9 ± 1 % of the mortar fraction of the mix (material passing the No. 4 sieve) is the optimum air content for concrete regardless of cement content or maximum size of the aggregate [14]. When the optimum air content is expressed as the air content of the entire mix the required air content will vary depending on the maximum size aggregate as shown in Table 1 [15].

TABLE 1.

Optimum air content of concretes containing different maximum size aggregates.

Maximum size of aggregate (in.).	Recommended average total air content (%).
3/4	6
1	5
1 1/2	4.5
2	4
3	3.5
6	3

CONTROL OF AIR CONTENT.

When air-entraining admixtures are used, it is very necessary to control the air content of the concrete within narrow limits to maintain uniform workability, strength and durability. Test for air content of the concrete should be made for control purposes during construction. The quantity of air-entraining admixture to be used should be adjusted, up or down, as required by results of the tests for air content of the concrete.

The pressure method of test [16] is the most suitable method for determining the air content of freshly-mixed concrete for large dams. Pres-

sure units having a capacity of 2.8 cu. ft. of concrete have been used to determine the air content of concrete containing 6-in. maximum size aggregates. Such large units are cumbersome to operate. It is the usual practice to wet-screen the concrete through a 1 1/2- or 3-in. sieve before testing when using concretes containing aggregate having a nominal maximum size of 3 in. or larger and then make the test in a smaller pressure unit. The wet-screening should be carried out with the minimum practicable disturbance of the mortar, no attempt being made to brush or wipe adhering mortar from the sieved-out cobbles [17].

TEMPERATURE RISE.

The use of air-entraining admixtures does not have any significant effect on the heat of hydration of portland cement per se. However, the use of air-entraining admixtures makes it possible to produce workable concrete with lower cement contents and the use of lower cement contents results in a smaller temperature rise within the mass.

Figure 3 shows the relative effect of cement type and cement content on the temperature rise of concrete cured under adiabatic conditions. The temperature rise of the concrete was calculated from heat of hydration data using an average value obtained from tests of six moderate heat of hydration (Type II) portland cements and four low-heat of hydration (Type IV) cements [18]. The neat cement pastes used for the heat of hydration tests were stored under conditions to simulate mass curing. Following this procedure the specimens were stored at 70 F. for one day and at 100 F. until the time of test or for an additional 27 days. Those used for tests at ages of 90 and 365 days were again stored at 70 F. after the 28th day. The heats of hydration were determined by the heat of solution method. The temperature rise of the concrete was calculated by assuming a water-cement ratio of 0.5 by weight and using 0.20 as the specific heat of the cement and aggregate.

The data shown in figure 3 indicate that both the type of cement used and the cement content of the concrete have a significant effect on the temperature rise. Comparing concretes of the same cement content (4 sacks/cu. yd.) the temperature rise is less for Type IV cement than it is for Type II cement. However, for concretes having a cement content of 3 sacks/cu. yd. or less, the temperature rise when using Type II cement is substantially less than that for the concrete having a cement content of 4 sacks/cu. yd. of Type IV cement. The use of a minimum cement content is one of the most positive and effective means of controlling temperatures in mass concrete.

CEMENT CONTENT AND CONSTRUCTION PRACTICES.

The thermal stresses and cracks in massive concrete, that are caused by temperature rise and subsequent fall within the mass, are well

known. The temperature rise is caused by the heat of hydration of the cement. An extensive investigation of cements for use in large dams was undertaken prior to the construction of Hoover Dam [19].

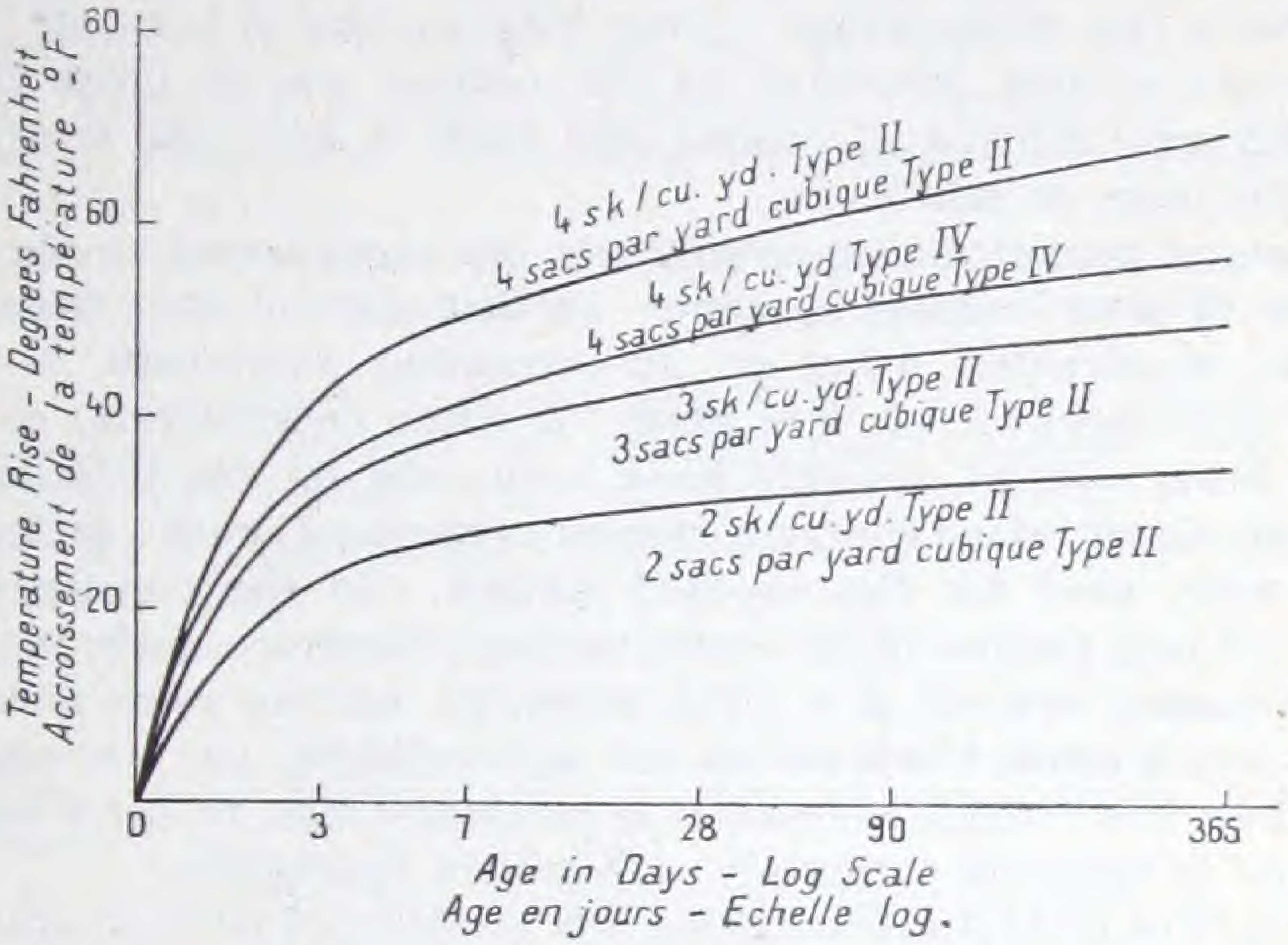

Fig. 3.

Relative effect of cement type and cement content on the temperature rise of concrete cured under adiabatic condition.

Effet relatif du type de ciment et de la teneur en ciment sur l'accroissement de la température du béton conservé dans des conditions adiabatiques.

Relative heat of hydration of type II and type IV Portland cements, average data. Neat cement pastes mass cured. Heat of solution data.

Chaleur d'hydratation relative du ciment Portland tyeeII et type IV. Moyennes des résultats. Pâte du ciment pure, conservée en masse. Valeurs de la chaleur de solution.

Age at test (days). Eprouvé à l'âge de (jours).	Heat of hydration (cal./g). Chaleur d'hydratation (cal./g). Type II.	Type IV.
3	57.9	47.5
7	70.2	55.5
28	80.1	68.9
90	84.2	71.8
365	90.8	79.4

Calculated from heat of hydration data for moderate heat of hydration (type II) portland cement, and low heat of hydration (type IV) portland cement.

Calcul basé sur la chaleur d'hydratation du ciment Portland à la chaleur d'hydratation modérée (type II) et du ciment Portland à chaleur d'hydratation basse (type IV).

These studies led to the development and production of low-heat (Type IV) portland cement for use in large dams. The first use of low-heat cement in the United States was in Morris Dam (originally

Pine Canyon), California, constructed in 1932-1933 by the Pasadena Water Department. A number of large dams was then constructed using low-heat cement, notably Hoover Dam, Shasta Dam and part of Grand Coulee. Concretes having a cement content of about 4 sacks/cu.yd were used in the construction. Even with the use of low-heat cement the amount of heat generated by the cement was so great that the embedded pipe method of cooling was used to keep the temperature rise in the mass at safe levels.

The use of air-entraining admixtures has contributed to the use of concretes of lower cement content. In that part of Blue Stone Dam that was constructed using an air-entraining admixture, a cement content of 3 sacks/cu. yd. was used. In later construction, concretes of even lower cement contents have been used for the interior mass. Even with air-entrained concrete, cement contents of about 4 sacks/cu.yd. are normally used for the exposed surface. In the construction of Pine Flat Dam, the use of an air-entraining admixture made it possible to use a cement content of 2 1/4 sacks/cu. yd. and for some part of the construction a cement content as low as 2 sacks/cu. yd. was used. To obtain these low cement contents it is necessary, also, to use a low sand factor and to maintain uniformly well-graded aggregates.

With the low cement contents that can be obtained with air-entraining admixtures, the heat of hydration of the cement becomes of less significance (*fig.* 3), and precooling becomes feasible in place of cooling by embedded pipes in large structures. The use of low-heat (Type IV) portland cement has been discontinued in the United States and moderate heat of hydration (Type II) cement is being used. The temperature rise in the mass is usually considered to be within safe limits without the use of embedded cooling coils if the concrete is precooled prior to placement. For precooled concrete, lift heights greater than the usual 5 ft. become feasible because cooling from exposed surfaces between lifts is of little consequence to subsequent temperatures. Lift height of 7 1/2 ft. were used on Table Rock Dam, Missouri, constructed by the U. S. Corps of Engineers, 1955 to 1958, with air-entrained concrete precooled to a maximum placement temperature of 50 F. The higher early strength of the Type II cement has a further advantage with respect to removal of forms when using concretes of very low cement content.

The use of air-entraining admixtures provides considerable economical advantage in the construction of large concrete dams through the use of lower cement contents and accompanying changes in construction practices.

REFERENCES.

1. H. F. Gonnerman, *Tests of Concretes Containing Air-Entraining Portland Cements or Air-Entraining Materials Added to Batch at Mixer* (*Proceedings, Amer. Concrete Inst.*, vol. 40, 1944, p. 477).

2. Charles E. Wuerpel, *Laboratory Studies of Concrete Containing Air-Entraining Admixtures* (*Proceedings, Amer. Concrete Inst.*, vol. 42, 1946, p. 305).

3. F. H. Jackson and I. L. Tyler, *Long-Time Study of Cement Performance in Concrete*; Chapter 7, *The New York Test Road* (*Proceedings, Amer. Concrete Inst.*, vol. 47, 1951, p. 773).

4. L. E. Andrews, *Record of Experimental Air-Entrained Concrete 10 to 14 Years After Construction* (*Highway Research Board*, Bulletin 70, 1953, p. 11).

5. *Standard Specifications for Air-Entraining Admixtures for Concrete* (*Amer. Soc. Testing Mat.*, 1955, Book of Standards, Part 3, p. 1279).

6. L. P. Witte and J. E. Backstrom, *Some Properties Affecting. The Abrasion Resistance of Air-Entrained Concrete* (*Proceedings, Amer. Soc. Testing Mat.*, vol. 51, 1951, p. 1141).

7. F. R. Mc Millan, *Study of Defective Concrete* (*Proceedings, Amer. Concrete Inst.*, vol. 27, 1931, p. 1039).

8. R. B. Young, *More Lessons from Concrete Structures in Service* (*Proceedings, Amer. Concrete Inst.*, vol. 27, 1931, p. 1065).

9. Axel Ekwall, *Deterioration by Aging of the Concrete in Gravity Dams* (*First International Congress on Large Dams*, Stockholm, Sweden, vol. 1, 1933, p. 203).

10. H. Eggenberger and A. Zwygard, *Decomposition by Aging of Concrete Used in Swiss Dams* (*First International Congress on Large Dams, Stockholm*, Sweden, vol. 1, 1933, p. 83).

11. H. F. Gonnerman, *Durability of Concrete in Engineering Structures* (*Building Research Congress*, 1951, England, Book of Papers, Division No. 2, Section D, Cement and Concrete, p. 92-104).

12. R. F. Blanks, *Ten-Year Report on the Long-Time Study of Cement Performance in Concrete* (*Proceedings, Amer. Concrete Inst.*, vol. 49, 1953, p. 601).

13. Roy W. Carlson, *Permeability, Pore Pressure and Uplift in Gravity Dams* (*Proceedings, Amer. Soc. Civil Eng.*, vol. 81, Separate No. 700, May 1955).

14. P. Klieger, *Studies of the Effect of Entrained Air on the Strength and Durability of Concretes Made with Various Maximum Sizes of Aggregates* (*Proceedings, Highway Research Board*, vol. 31, 1952, p. 177).

15. *Recommended Practice for Selecting Proportions for Concrete* (A. C. I. 613-54) (*Proceedings, Amer. Concrete Inst.*, vol. 51, 1954-1955, p. 49).

16. *Standard Method of Test for Air Content of Freshly-Mixed Concrete by the Pressure Method* (*Amer. Soc. Testing Mat.*, 1955, Book of Standards, Part 3, p. 1287).

17. *Method of Test for Air Content of Freshly-Mixed Concrete*, (C. R. D.-C 41-52) (*Handbook for Concrete and Cement*, Waterways Experiment Station, Corps of Engineers, U. S. Army).

18. William Lerch and C. L. Ford, *Long-Time Study of Cement Performance in Concrete*, Chapter 3, *Chemical and Physical Tests of the Cements* (*Proceedings, Amer. Concrete Inst.*, vol. 44, 1948, p. 745).

19. Raymond E. Davis, R. W. Carlson, G. E. Troxell and J. W. Kelley, *Cement Investigations for Boulder Dam with the Results up to the Age of one Year* (*Proceedings, Amer. Concrete Inst.*, vol. 30, 1934, p. 485).

SUMMARY.

Laboratory studies of air-entraining admixtures and air-entrained concrete were initiated in the United States about 1937. As the properties of air-entrained concrete became established, it was apparent that such concrete had many technical and economical advantages for use in large dams. The first use of an air-entraining admixture in a large dam in the United States, to produce purposeful air-entrained concrete of controlled air content, was in 1946. The use of air-entraining admixtures has increased rapidly since that time and such admixtures have been used in all large concrete dams constructed in the United States in recent years. The performance of air-entrained concrete has fully justified its use. The use of air-entraining admixtures improves the workability of concrete and has made it possible to place concretes of lower cement content in the construction of large dams. The resultant use of lower cement contents decreases the temperature rise within the mass and has likewise brought about some change in the type of cement used in the construction of large dams in the United States.

The paper discusses the technical and economical aspects of the use of air-entraining admixtures in large concrete dams.

RÉSUMÉ.

Des essais en laboratoire ayant pour but de déterminer les propriétés et le rôle des agents dispersifs à entraînement d'air et du béton à l'air occlus ont été effectués aux États-Unis depuis 1937. Lorsque les propriétés des bétons aérés furent définies, il devint évident que ce béton présentait beaucoup d'avantages pour son emploi dans les grands barrages. L'addition des agents aérateurs fut utilisée pour la première fois aux États-Unis en 1946, lors de la construction d'un grand barrage afin de produire un béton ayant une teneur d'air entraîné bien contrôlée. L'emploi des mélanges aérateurs s'est augmenté depuis cette date et ces produits sont utilisés dans tous les grands barrages exécutés récemment aux États-Unis. Le comportement du béton avec addition d'agents entraîneurs d'air a justifié son emploi. L'utilisation de ces agents aérateurs conduit à une amélioration de la maniabilité (workability) du béton, et a rendu possible l'emploi de béton de mettre à plus faible teneur en ciment pour la construction de grands barrages. Il résulte de l'emploi de bétons à faibles teneur en ciment un abaissement de la température à l'intérieur du massif et cela a conduit à des modifications dans les types de ciments employés dans la construction des grands barrages aux États-Unis.

La présente communication est une analyse des aspects techniques et économiques de l'emploi des agents aérateurs dans les grands barrages en béton.

Extrait du *Sixième Congrès des Grands Barrages.*
New York, 1958.

152903-58 Paris. — Imp. GAUTHIER-VILLARS, 55, quai des Grands-Augustins.
Imprimé en France.